

GOING BELOW MINIMUMS: THE EFFICACY OF DISPLAY ENHANCED/SYNTHETIC VISION FUSION FOR GO-AROUND DECISIONS DURING NON-NORMAL OPERATIONS

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The use of enhanced vision systems in civil aircraft is projected to increase rapidly as the Federal Aviation Administration recently changed the aircraft operating rules under Part 91, revising the flight visibility requirements for conducting approach and landing operations. Operators conducting straight-in instrument approach procedures may now operate below the published approach minimums when using an approved enhanced flight vision system that shows the required visual references on the pilot's Head-Up Display. An experiment was conducted to evaluate the complementary use of synthetic vision systems and enhanced vision system technologies, focusing on new techniques for integration and/or fusion of synthetic and enhanced vision technologies and crew resource management while operating under these newly adopted rules. Experimental results specific to flight crew response to non-normal events using the fused synthetic/enhanced vision system are presented.

Introduction

Synthetic vision (SV) is a computer-generated image of the external scene topography that is generated from aircraft attitude, high-precision navigation, and data of the terrain, obstacles, cultural features, and other required flight information. A synthetic vision *system* (SVS) enhances this basic functionality with real-time integrity checks to ensure the validity of the database, obstacle and navigation accuracy identification and verification, and continuous traffic surveillance functions. An Enhanced Vision (EV) System, EVS, (also referred to as an Enhanced Flight Vision System) is an electronic means to provide a display of the external scene by use of an imaging sensor, such as a Forward-Looking InfraRed (FLIR) or millimeter wave radar. The intended use of EV mirrors SV – both strive to eliminate low-visibility conditions as a causal factor in civil aircraft accidents and to replicate the operational benefits of clear day flight operations, regardless of the actual outside visibility condition. The methodology by which this capability is achieved through SV or EV, however, is significantly different. While some may consider the technologies to be competing; they are, in fact, complementary.

SV, by virtue of being weather-independent and unlimited in field-of-regard, holds many advantages over enhanced vision sensor systems for providing terrain, path, and obstacle awareness, particularly during flight phases, such as approach, which may be obscured by clouds and precipitation that an EV sensor cannot penetrate. Recognition of terrain and cultural features may also be improved over an EV view since the display presentation is optimized by the display

designer, not the product of the sensor and its environment. Pilot recognition of EV terrain and cultural features depends upon the reflected, emitted, and / or refracted energy at the spectral frequencies of the EV sensor and the ability of the pilot to (correctly) interpret this image. Atmospheric effects, time of day, and sensor characteristics can be important factors in the quality of the EV imagery.

On the other hand, EV is an imaging sensor which provides a direct view of the vehicle external environment; consequently, EV is completely independent of the derived aircraft navigation solution and is independent of a database. Very little stands between the EV image shown to the pilot and the real-world; thus, an EV pilot gets an extremely high degree of confidence in the system. Under conditions of smoke, haze, and night, a FLIR/EV may provide orders-of-magnitude improvement over the pilot's natural vision; greatly enhancing the pilot's situation awareness and reducing the pilot's workload.

Previous synthetic vision research (Parrish et al., 2003) has shown that a "flight-critical" synthetic vision implementation which uses automated decision aiding functions for object detection and database alignment/navigation error detection produces superior performance to synthetic vision concepts with an EV inset display (e.g., McKay et al., 2002). To date, however, technology for "perfect" object detection and database/navigation error detection does *not* exist. Further, even if these systems come to fruition, there may still be gaps, such as minimal radar cross section objects or below-threshold detection values, which may require other additional integrity and error checks. SV with EV inset displays *may* offer one possible method to provide

the pilot with information sufficient to perform navigation integrity and obstacle clearance checks.

While EV might improve SV operations, the converse warrants investigation as well. In 2004, Section §91.175 of the Federal Aviation Regulations was amended such that operators conducting straight-in instrument approach procedures may now operate below the published Decision Height and Minimum Descent Altitude when using an approved Enhanced Flight Vision System (EFVS) on the pilot's Head-Up Display (HUD). This rule change now provides "operational credit" for EV. As such, EV operations will become more prevalent. However, while EV may help with the "last 100 ft", it may not supplement the pilot's awareness of the terrain, obstacles, and flight path much outside of this area. SV may fill in this awareness "gap," (i.e., before the EV sensor provides a useful image) and it may also provide the crew with "visual momentum" to assist the crew's understanding and correct interpretation of the EV sensor imagery.

An experiment was conducted to evaluate the complementary use of SV and EV technologies, specifically focusing on new techniques for integration and/or fusion of synthetic and enhanced vision technologies and crew resource management while operating under the newly adopted FAA rules which provide operating credit for EV. The overall objective of this experiment was to test the utility, acceptability, and usability of integrated/fused enhanced and synthetic vision systems technology concepts in two-crew commercial and business aircraft cockpit for Required Navigation Procedures (RNP)-type approaches; these results are described in Bailey, Kramer, and Prinzel (2006). The current paper describes experimental results specific to flight crew response to non-normal events that were staged in this experiment using a fused synthetic/enhanced vision system.

Methodology

Subjects

Twenty-four pilots, representing seven airlines and a major cargo carrier, participated in the experiment. All participants had previous experience flying HUDs. The subjects had an average of 1787 hours of HUD flying experience and an average of 13.8 years and 16.2 years of commercial and military flying experience, respectively.

Simulator

The experiment was conducted in the Integration Flight Deck (IFD) simulation facility at NASA Langley Research Center (LaRC). The IFD emulates a Boeing B-757-200 aircraft and provides researchers with a full-mission simulator capability. The collimated out-the-window (OTW) scene is produced by an Evans and Sutherland ESIG 4530 graphics system providing approximately 200 degrees horizontal by 40 degrees vertical field-of-view at 26 pixels per degree. Traditional primary flight and navigation displays were presented head-down.

Head-Up Display

The HUD subtended approximately 32° horizontal by 24° vertical field of view. The HUD presentation was written strictly in raster format from a video source (RS-343) input. The input consisted of a video mix of symbology and computer-generated scene imagery (either EV or SV as described in the following). The symbology included "haloing" to ensure the readability of the symbology against the background scene imagery background. Brightness and contrast controls were provided to the pilot. Also, the pilot had a declutter control, implemented as a push-button on the left hand horn of the Pilot Flying (PF) yoke. The button cycled through three "declutter" states: 1) No declutter (full symbology and scene imagery); 2) "Raster" declutter (full symbology, no scene imagery); and 3) "Full declutter" (no HUD display).

Four HUD display concepts were tested, differing from each other in: 1) the type of raster background presented; and, 2) in the type of symbology presented. Two raster formats were flown, either EV only (hereinafter referred to as "FLIR") or a fusion SV/EV image (hereinafter referred to as "Fusion."

The FLIR-only concept represented our "baseline" EFVS HUD condition. The Fusion HUD concept represents one method of providing complementary SV/EV information for the pilot flying. The Fusion HUD raster image started out as a pure SV image, transitioning through a fused SV/EV presentation beginning at 600 feet above ground level (AGL), and ending with a pure FLIR raster image by 500 feet AGL. Between 600 feet and 500 feet AGL, the fusion gradually stepped from 100% SV / 0% EV ending at 0% SV / 100% EV. Each raster concept showed FLIR below 500 ft to take advantage of the operational credit now offered by use of FLIR on the HUD. The 500 ft Fusion transition altitude was chosen from a prior usability study designed to assess an optimum altitude after which FLIR would be required.

As mentioned earlier, two symbology sets were flown: Standard HUD symbology (hereafter referred to as

“Baseline”) and the same standard HUD symbology enhanced with pathway guidance and a runway outline (hereafter referred to as the “Tunnel” symbology set). The “tunnel” symbology set was tailored to transition at the same altitudes as the Fusion raster and this transition was based on flight test experience (Kramer et al., 2005). The tunnel was shown above the 500 ft Above Field Level (AFL) transition altitude, the last tunnel segment was positioned at 500 ft AFL (thus, it was no longer visible below 500 ft), and, upon reaching 500 ft AFL, the runway outline was drawn until 50 ft AFL. In Figures 1 and 2, two of the concepts are shown, the Fusion-Tunnel HUD and the FLIR-Baseline HUD.



Figure 1. Fused HUD Concept with Tunnel



Figure 2. Baseline HUD Concept (EV Only)

Auxiliary Display

The Pilot Not Flying-Auxiliary Display (PNF-AD) was located outboard of the PNF location which is not atypical of modern Boeing commercial aircraft electronic flight bag display installations. The 8.4" diagonal display was full-color with 1024 x 768 pixel resolution. The display video source was a video mix of symbology and computer-generated scene imagery.

Four PNF-AD display concepts were tested, differing from each other in: 1) the type of raster background

presented; and, 2) the type of symbology presented. The raster was either EV only (hereinafter referred to as FLIR) or a fused SV/EV image (hereinafter referred to as Fused). The symbology was either “On” or “Off” for the data runs. When present, the symbology was a subset of the standard HUD symbology (Figures 3 & 4).



Figure 3. EV Only – No Symbology



Figure 4. Auxiliary Display Fusion – Symbology

The AD fused raster image was pilot-controllable and could be tuned throughout the approach to one of 10 states: FLIR only, SV only, or 8 fusion combinations of FLIR and SV, using an Equinox EP-3000™ fusion board. The fusion employs a feature-level extraction algorithm with two pilot control inputs: (1) feature-level fusion of FLIR and SV and (2) modulation of false-color coding of the fusion image.

Synthetic Vision System

A synthetic vision database was created from a 1 arc-sec (30 meter post-spacing) Digital Elevation Model (DEM) of a 53 x 53 nm area centered around the Reno-Tahoe International Airport (FAA identifier: KRNO). The airport was represented by three-dimension models of the runway, taxiways, and terminal buildings. The DEM was draped with 1 meter/pixel satellite imagery within a 16 x

21 nm area centered around KRNO and 4 meter/pixel outside this inner region.

Enhanced Vision System

A physics-based FLIR simulation (using Evans & Sutherland EPX Sensors™) was created from the OTW visual database by applying materials properties to each component of the data. The characteristics of a short/mid-wave FLIR were simulated in a “white-hot” presentation. The time-of-day, time-of-year, and other diurnal properties were held constant. Atmospheric properties (cloud layer, cloud height and thickness, fog, and visibility) were varied experimentally to modulate the visibility that the evaluation pilots had in the FLIR and the OTW scene presentations.

Evaluation Task

The PF hand-flew the base and final leg portions of the Sparks Visual Arrival to RNO Runway 16R with autothrottles engaged at an approach speed of 138 knots. The PNF monitored the approach from the right-hand side of the flight deck using standard instruments and the AD. This high workload, curved descending approach (currently approved for visual conditions only) was chosen to evaluate the use of SV/EV technologies for performing an RNP-type approach while flying in restricted visibility. The aircraft was configured for landing prior to each run (landing gear down and flaps 30 degrees). Pilot participants were instructed that the run would end at main gear touchdown but that they should perform a go-around if they felt the landing was not safe or if they did not have the required visual references to descend below decision height or to complete the landing as per FAR §91.175.

Experiment Matrix

Nominally, 42 experimental runs were completed by the evaluation crew with each pilot flying 21 approaches evaluating the HUD concepts and with each pilot monitoring 21 approaches while evaluating the AD concepts. The wind and weather varied on each run. The nominal visibility in the EV and OTW varied from 1 mile down to $\frac{1}{2}$ mile. The required EV visual references as per FAR §91.175 became visible on the HUD between 450 ft and 250 ft AFL, enabling the crew to descend to 100 ft Height Above Touchdown (HAT). 4 runs per flight crew were specifically designed so the EV visual references were visible but the required runway (normal vision landing) references were not. These four runs, if properly flown using the EV crew procedures, should conclude by a go-around initiated no lower than 100 ft AFL.

Six non-normal runs were also flown by each crew. The non-normals were runway incursion (RI) scenarios (2 per crew) and database integrity monitoring scenarios (4 per crew). The low number of RI and database integrity scenarios precluded expectancy on the part of the flight crew. The RI scenarios simulated an incursion with either a non-transponding baggage cart or fire truck. The database integrity monitoring scenarios purposefully introduced a lateral navigation solution error (of either 50 or 75 feet) with respect to the real runway. This error resulted in the synthetic vision terrain, pathway and guidance cue being misaligned from the FLIR and ILS (which were defined in the flight crew briefing as always being correct).

Procedure

The subjects were given a 1-hour briefing to explain the SV/EV display concepts, EV crew procedures, and the expected evaluation tasks. After the briefing, a 2-hour training session in the IFD was conducted to familiarize the subjects with the aircraft handling qualities, display symbologies, SV/EV crew procedures, and controls. Special emphasis was placed on the 91.175 regulations pertaining to EV operations. The ‘rare-event’ scenarios were not discussed, although the pilot’s responsibility for maintaining safe operations at all times was stressed. Data collection lasted approximately 4.5 hours followed by a 30-minute semi-structured interview. The pilots were also given a final questionnaire.

Results

Nominal Run Results

Experimental data was taken for flight technical error, mental workload, and situation awareness during all runs. The results are reported in Bailey, Kramer, and Prinzel (2005) and only the general findings are discussed below.

Path Control Performance. Root-mean-square (RMS) lateral and vertical path error performance followed previous studies. The presence of a tunnel significantly enhanced flight technical performance during approach phase. The performance differences may not be operationally significant however. No effect was found for HUD raster type.

Mental Workload. Mental workload was assessed after each experimental run, using the AFFTC workload estimate tool, and post-test, using SWORD. Pilots reported significantly lower post-run mental workload ratings for the combination of fused raster type and tunnel on the HUD. No significant differences were found for the PNF-AD configurations. Post-test, pilots reported no workload differences for the HUD concepts

yet significantly lower workload ratings for the fused raster with symbology PNF-AD condition.

Situation Awareness. Situation awareness was assessed after each experimental run, using SART, and post-test, using SA-SWORD in both PF and PNF roles. Pilots reported significantly higher post-run ratings when the tunnel was paired with fusion raster type on the HUD. No significant differences for symbology and raster type was found on the PNF-AD. The post-test results mirrored those of the post-run data for the HUD concepts. Post-test, the pilots ranked the Fused-Symbology PNF-AD concept as having significantly higher SA than the other concepts.

Rare-Event Results

Runway Incursions. The runway incursions were made by a baggage cart and a fire truck. Both items were positioned in the same location, approximately 850 ft from the RNO16R landing threshold and just slightly offset from the centerline. The weather on the runway incursions was held constant at 2400 ft runway visual range (RVR) OTW with the lowest cloud layer at 500 ft AFL. The FLIR visibility was very good in this condition – approximately 4 times the OTW RVR.

The baggage cart runway incursion was always performed before the fire truck incursion. The baggage cart was much more difficult to see due to its small size. This ordering tested for “just noticeable differences” for runway incursion detection. For the 12 flight crews, only one crew saw the baggage cart (observed OTW by the PNF), but all 12 crews saw the fire truck. Eleven crews saw the fire truck OTW (7 by the PNF, 3 by the PF, and 1 simultaneously by the PF and PNF) and one crew saw it on the PNF-AD. Upon seeing the incursions, all crews initiated a go-around (all lower than 50 feet AGL).

Navigation Error. The navigation errors were either a 50 foot or 75 foot lateral offset (Figure 5). The offsets could be detected by either the PF or the PNF. The errors were noticeable from one of several principle ways (depending upon the display configuration):

- By a disagreement between the lateral path error and the localizer deviation symbology (HUD and PNF-AD with symbology).
- By a non-zero localizer deviation on the PFD when the PF is flying on the final approach path centerline.
- By differences between the SV and the EV registration using the PNF-AD Fusion controls.

- By differences between the runway outline and the EV imagery of the runway (HUD and PNF-AD).
- By differences in the pitch/roll guidance symbol and the EV imagery (PF-HUD and PNF-AD)



Figure 5. 75 foot localizer offset

The majority of flight crews verbally noted the presence of the 50 foot offset (15/24) and 75 foot offset (22/24) during the approach. None of the pilots executed a go-around with this anomaly. Each performed a lateral correction and landed near the runway centerline. Video analysis showed that navigation errors were predominately noted by the PF (~85%) when they noticed that the pitch/roll guidance symbol was leading them to the left or right of the runway. One person (flying as the PNF) noted the non-zero localizer deviation on the PFD presentation while tracking the path centerline.

Illegal Landings

Each flight crew was confronted with four trials where weather conditions obscured the visual cues required to complete the landing from 100 ft HAT as defined by FAR §91.175. Of the 48 “illegal landing” rare event trials, only during six of these trials did pilots continue and land the aircraft. (See Table 1.)

Discussion

Runway Incursions

The incurring vehicles were visible in the PNF-AD and HUD, yet the data suggests that EV on the HUD and PNF-AD were not useful for RI detection. In the HUD, the incurring vehicles were largely occluded by symbology on the HUD (flight path marker and guidance cue) and the small size and relatively low resolution of HUD made vehicle detection extremely difficult for the PF.

In contrast, the vehicles were much more apparent in the PNF-AD. Again, the vehicle size and contrast to the surroundings made detection on the PNF-AD moderately

difficult above 200 ft AFL, particularly if the PNF only used cursory looks at the PNF-AD. The presence of symbology on the PNF-AD could also obscure the vehicles. Below 200 ft AFL, the vehicles were much more obvious in the image, but the PNF was head-out the vast majority of the time, ranging from 86% to 100% of the total time below 200 ft. AFL.

The display concepts tested in this experiment – typical of current and future PF HUD and PNF-AD displays – showed poor incursion detection functionality. Only one of the runway incursion scenarios was detected through use of the cockpit displays. Therefore, requirements for display and sensor technology for runway incursion detection should be developed. The requirements for this function should span the breadth of the problem, including human perception, sensor design and detection theory, crew procedures, and crew interface issues.

Table 1. Illegal Landing Trials

| Crew | Observation | HUD | AD |
|------|---------------------------------------|-------------------|--------------------|
| 3 | Go-around considered | FLIR No Tunnel | Fused No Symb. |
| 4 | Threshold lights called at 80 ft AFL | FLIR No Tunnel | FLIR/ Symbology |
| 4 | Threshold lights called at 60 ft AFL | FLIR No Tunnel | Fused Symbology |
| 7 | Threshold lights called at 100 ft AFL | FLIR Tunnel | Fused Symbology |
| 8 | Threshold lights called at 120 ft AFL | FLIR No Tunnel | Fused No Symb. |
| 11 | Threshold lights called at 90 ft AFL | FLIR No Tunnel | FLIR No Symb. |

Navigation Error

The flight crews were not instructed on the course of action to take when confronted with a navigation error, and these pilots had relatively little training and experience with the system. Despite this, the study showed that lateral navigation errors were verbally acknowledged a significant percentage of time and, even when unrecognized (i.e., not explicitly verbalized), all flight crews landed safely and accurately on the runway. These results suggest that dissociations between raw data, sensor, and/or database presentation should be easily recognized and managed by experienced pilots. Pilot training to recognize these discrepancies could further improve operations in the event of this anomaly.

Illegal Landings

The results demonstrated the potential for flight crews to continue approaches to a landing during visibility

conditions that instead require a go-around under the new 91.175 operational rules for EFVS. On each of the six illegal landings, the pilot flying had excellent visibility of the runway using the FLIR on the HUD. However, the 91.175 rule requires visual acquisition of the runway references without use of the EFVS. No effect of symbology type on the HUD was observed. The operational procedures necessary to follow the 91.175 regulation was found to be awkward for the PF, requiring the PF to declutter the HUD or look-around the HUD combiner. The radio altitude shown on the HUD could be used for judging HAT.

For the PNF, conformance to the 91.175 required visual references was not influenced by the PNF-AD configuration. The PNF had to go head-down to read the altitude on the PFD or PNF-AD. The experiment did not use a “100 ft” AFL call-out.

The few occurrences of “below minimums” landings suggest that the current regulations can be operationally viable. However, an aural call-out at 100 ft AFL may help overcome the lack of awareness to the HAT. Nonetheless, there still exists an awkwardness in the transition from EV/HUD-to-visual runway references. The PFs typically commented that the EFVS provided suitable visual references to complete the flare and landing.

References

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